Thermodynamics of light at the nanoscale – a stochastic thermodynamics approach to coherent energy exchanges between lasers and atoms

What is the thermodynamics of light interacting with quantum systems? Despite the widespread use of light in science, the thermodynamics of the fluctuations of photons at the nanoscale is still ill understood, especially far from equilibrium and/or in the presence of quantum coherent effects.
A powerful theory for energy fluctuations in small, complex, and far from equilibrium systems has emerged in the past two decades, stochastic thermodynamics [1], which was successfully used for electronic, colloidal and biological systems. One of the main achievements of the theory is the derivation of fluctuation theorems, expressed as a symmetry relating entropy or energy fluctuations generated during a given forward process with the fluctuations of the time reversed process. Fluctuation theorems imply that, regardless of the complexity of the system, the dynamics are constrained to obey a universal symmetry. The even more recent field of quantum stochastic thermodynamics aims at extending these ideas to quantum systems, the main challenge being to account for coherent effects and entanglement.

In this talk, I will present our recent results, in the direction of building a framework for the thermodynamics of light-matter interactions at the fluctuating level and far from equilibrium.
Central to stochastic thermodynamics is the notion of thermodynamic consistency: every thermodynamic quantity obtained from the stochastic dynamics should have a thermodynamic interpretation which is justified at the microscopic scale. On the other hand, a widespread approach to open quantum systems is to derive quantum master equations describing the reduced dynamics of the system after tracing out its environment. A thermodynamically consistent quantum master equation should therefore preserve the symmetries of the fluctuation theorems. Our first main result [2] is the identification of a new generalized quantum detailed balance condition which quantum master equations must satisfy in order to be thermodynamically consistent. We then focus of the case of coherent energy exchanges between lasers and atoms. The second main result [3] is the derivation of a fluctuation theorem for the energy transferred from a laser to an atom, valid even in the strong light-matter coupling regime. We then examine the thermodynamic consistency of master equations describing the dynamics of an atom coherently driven by a laser – the optical Bloch master equation and the Floquet master equation. We find that the Floquet master equation is fully consistent, i.e., satisfies the first and second laws of thermodynamics at the fluctuating level, while the Bloch equation is only consistent at the average level.

[1] U. Seifert. “Stochastic thermodynamics, fluctuation theorems and molecular machines”. Reports on progress in physics, 75(12):126001 (2012)
[2] A. Soret, V. Cavina, M. Esposito. “Thermodynamic consistency of quantum master equations”, Phys. Rev. A, 106:062209 (2022)
[3] A. Soret, M. Esposito. “Thermodynamics of coherent energy exchanges in quantum optics”. (draft in preparation)